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A COMPARISON OF REEF-PROTECTED ENVIRONMENTS IN WESTERN AUSTRALIA: THE CENTRAL WEST AND NINGALOO COASTS

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ABSTRACT

Variability in the regional setting and morphology of cuspate forelands on the west coast of Western Australia is examined in this paper. In accordance with this aim, principal differences in the geologic and geomorphologic setting of three prominent sites on the west coast were established and their association with historical changes and contemporary oceanographic processes was examined. The cuspate forelands investigated are Jurien Bay, Winderabandi Point and Turquoise Bay. The most significant differences in geologic setting are associated with the structure and location of an extensive offshore reef system. Morphologically, the reef alters from south to north, changing from a discontinuous ridge parallel to the shore along the central west coast, to a nearly continuous fringing reef at Ningaloo. The reefs vary in distance from the shore, being farthest in the south and closest in the north and they impound a series of inshore basins, or lagoons. The deeper southern basins are dominated by locally generated wind waves and wind-generated currents. The shallower northern basins are most markedly affected by tidal currents and wave pumping across the reef flats.

The large cuspate foreland at Jurien on the central west coast has undergone shoreline configuration change in response to changing phases of storminess as well as in response to a change in focus for sediment deposition as a result of offshore reef erosion. At Winderabandi Point on the Ningaloo coast, relict Pleistocene limestone has provided the focus for sedimentation and morphology has been controlled by a balance in refracted wave energy and nearshore currents driven by tidal and wave set-up variability. At Turquoise Bay, where the lagoonal basin is most shallow and narrow, the morphology of the foreland suggests that it may at some stage have been migratory, but its present asymmetrical shape is maintained by strong northerly longshore drift and strong currents exiting the lagoon through a nearby gap in the reef crest. Fundamental differences between the two coastal regions include the structure of the offshore reef, processes driving flow of water within the lagoons and the role of storminess in evolution of coastal landforms. Although many questions regarding storm surge dynamics and landform change remain unanswered, this research provides a significant contribution to the understanding of the evolution of morphological systems in low-wave-energy protected environments. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: cuspate foreland; tombolo; coast; Western Australia; reefs

INTRODUCTION

The main aim of this research is to establish broad relationships between the variability in geomorphology, the historical evolution of cuspate forelands, and their hydrodynamic settings on the west coast of Western Australia. Sanderson and Eliot (1996) established that the geometries of accretionary landforms and their morphological relationship with natural offshore structures could be used to distinguish between local coastal regions. Cuspate forelands and tombolos on the south coast of Western Australia (Figure 1) have formed by deposition of sediment resulting from the convergence of swell behind an obstacle, usually an island or prominent headland. Similar forms have been described by Zenkovich (1967), Hoyt and Henry (1971), King (1972) and Kraft *et al.* (1979). In contrast to this, submerged reefs along the central west and Ningaloo coastal regions provide an offshore barrier to incoming swell that would normally transport sediment onshore. Complex diffraction and refraction of the swell take place and sediment is deposited in a less predictable manner but still leads to the formation of cuspate forelands and shoreline salients in the lee of the reef system

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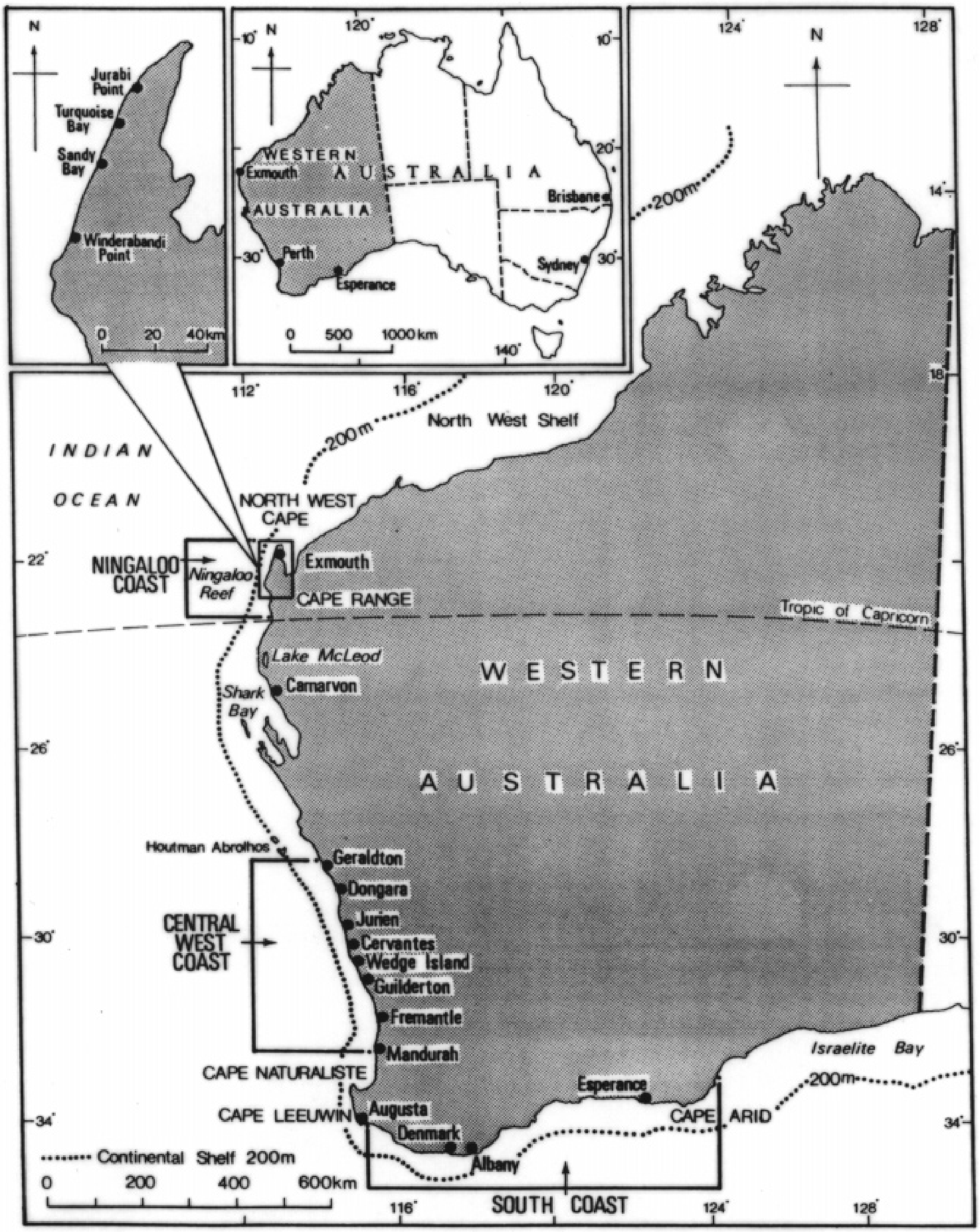

Figure 1. Western Australian coastal environment

and offshore islands (Semeniuk *et al.*, 1988; Sanderson and Eliot, 1996). Flushing of lagoonal waters landward of the reefs appears to impede the formation of tombolos and provides part of the explanation for morphological variability. Shelf-wave and other non-tidal fluctuations in sea level are relatively significant processes along the coast due to attenuation of swell energy by the offshore reef systems. Previous descriptions of similar forms include those by Escoffier (1954) and Downs *et al.* (1994). The process and morphologic settings for landforms of the central west and Ningaloo coasts thus form the focus of this paper because of their marked contrast with those of the south coast.

Prior to the regional investigations of Sanderson and Eliot (1996), most studies of landforms on the Western Australian coast focused on the stratigraphy or sedimentology of a specific formation (e.g. Semeniuk and Searle, 1986; Semeniuk *et al.*, 1988), rather than on the broad relationships between morphology and regional processes. This paper presents a preliminary characterization of the central west and Ningaloo coastal environments in terms of lagoonal topography, nearshore processes and associated accretionary landforms. More specifically, the objectives of this research are to:

1. review the geological development of the forelands during the Holocene;
2. determine shoreline movement and change in morphology of the forelands over the period for which historical records are available;
3. identify the principal hydrodynamic processes operating in both regions;
4. relate the hydrodynamic processes to contemporary shoreline configuration and nearshore morphology;
5. establish potential relationships between the historical changes and the contemporary morphodynamics of the forelands as a first step to determining the degree to which the forelands are changeable and the conditions under which they evolve; and
6. compare the contemporary processes acting on the forelands, historical changes to them and the current understanding of their geological development as a basis for explanation of regional diversity in landform development.

CONTEXT

Sedimentary landforms characterize many of the world's coastlines (Bird and Schwartz, 1985). Originally, the term 'foreland' was applied to the Dungeness foreland in Britain (Gulliver, 1896, 1899) and 'tombolo' was used to describe a spit of sand or shingle which joins a bedrock outcrop to the neighbouring coast (Harris, 1968). It has since been recognized that low amplitude shoreline salients, cuspate forelands and tombolos are part of a hierarchy of coastal sedimentary landforms (Horikawa, 1988). Cuspate forms are often termed salients when they are of small scale, in their formative stages of development, or when discussed in the context of engineering applications (Silvester and Hsu, 1993).

Early descriptions of the cuspate shorelines define the landforms and their environmental settings. Genetic classifications of coastal landforms have been made (Zenkovich, 1967; King, 1972). However, they relate to general oceanographic or coastal settings rather than focusing on individual landforms, or groups of landforms. The descriptions deal with the morphology and genesis of the subaerially evident part of the accretionary form and few studies concentrate on contemporary processes maintaining a sediment supply to the coastal area or on the processes affecting erosion. More recent research examined individual forms and broadscale processes associated with their evolution. Brief attention has been given to the general morphology of individual cuspate and tombolo features at a variety of locations around the world (Bird, 1985a,b; Fisher, 1985; Jackson, 1985; Pitman, 1985) and much of this literature indicates that tombolos and cuspate forelands are associated with deltas, tombolo settings, or spit/barrier coasts (Guilcher and King, 1961; Yasso and Fairbridge, 1968; Hoyt and Henry, 1971).

Examination of the environmental settings of cuspate forms has also been made through stratigraphic investigation of individual landforms. The variety of stratigraphic sequences described is shown to reflect their diverse origins (Johnson, 1919; Fisher, 1955; Russell, 1958; Zenkovitch, 1959; Hey, 1967; Kraft, 1971; High, 1975; Kraft *et al.*, 1979; Pitman, 1985). Johnson's (1919) description of cuspate foreland morphology

centred on progradation of beach ridges and intervening swales, in which truncation of older ridges may occur. These cuspate forms often enclosed marsh/swamp environments and this was also reflected in the stratigraphy. Fisher (1955) described large cuspate spits of St. Lawrence Island, Alaska, as being built by longshore drift of beach sand and modification by lagoon currents. A number of origins of the spit formations was suggested, including: deposition by opposing eddy currents: deposition within wave shadows; longshore drift building a series of recurved points on a spit with later modification by waves; repeated breaching of the lagoon barrier beach with deposition of sediment washed through the opening; and the development by currents deflected or modified by sediment masses washed over the barrier beach during storms. Zenkovitch (1959) commented that cuspate spits with a similar morphology could be found on the Chukotsky Peninsula, USSR; however, they were built of coarse material and were found only in narrow bodies of water. He suggested that investigation of the origins of these forms required study of their historical and longer-term development, as it was unclear which processes were responsible for their formation. From his work, it is anticipated that examination of long-term changes in landform morphology would also be required to gain an understanding of the processes driving evolution of cuspate forelands and tombolos in Western Australia.

A wider-scale approach to examination of the formation of cuspate forelands was used by Hey (1967) in investigation of the stratigraphy of the Dungeness Foreland. He reported loose shingle overlying gravels packed with sand, grading to stoneless sand with marine shells at the base of the section through the foreland. It was suggested that the more pebbly deposits were laid down on an actively prograding foreshore where there was a very large sediment supply. He postulated that the shingle deposits may have been built during storms, when higher energy conditions were able to transport coarse material onto the back of the beach. His consideration of the effects of sediment supply to the coast included a suggestion that the supply of material may have been too rapid to allow large-scale erosion to occur, thus leading to continued progradation of the foreland.

Snead (1982) described cuspate forelands as growing during severe storms when there is a greater movement of material. When currents or storm waves meet from two different directions, the shore is aggraded on both sides so that fairly symmetrical lines of growth consisting of beach ridges and swales run parallel with both shores of the cusp, forming a simple cuspate foreland. Whether this is the case in Western Australia, where phases of storminess lasting 5 to 10 years are separated by 20 to 30 year periods of calmer conditions (Panizza, 1983), remains open to investigation through systematic monitoring and/or examination of detailed historical records such as charts and aerial photographs.

The influence of human activities on landform evolution was considered by Kraft (1971) and Kraft *et al.* (1979) in their discussion of the evolution of a cuspate foreland on Cape Henlopen in Delaware. They proposed that while littoral drift of sands was forming and extending the gravel spit sequences already present, human intervention played a major role in the development of the cuspate foreland due to diversion of longshore drift and sediment supply by the construction of a harbour. The gravels reported in the area were shown to overlie estuarine silts and clays suggesting a diversity of conditions, both natural and human-induced, during formation of the cuspate landform assemblage.

Where many of these studies report the importance of longshore drift in development of cuspate forelands, few consider the role of storms in progradation or erosion of the coast. It may be suggested, however, that storm conditions could induce significant change in landform morphology and therefore play an important role in the evolution of the landforms. High (1975) does suggest that sedimentation along the coast of Belize takes place during storms, in a manner similar to that suggested by Hey (1967). On the Belize coast, which is well protected by an offshore barrier reef system, sediment is provided by longshore currents but compartmentalization of the coast leads to possibly two or more sets of wind-driven storm waves which interfere with each other as they approach the coast (High, 1975). Consequently, cuspate forelands in Belize are characteristically formed by the growth of two sets of beach ridges, or spits, which meet in a point.

In the above studies of cuspate forelands, a number of mechanisms for formation of cuspate forelands and tombolos are suggested from their morphology and stratigraphy. Longshore drift was proposed by Fisher (1955) as forming forelands, following modification of the longshore drift by lagoon currents. Opposing wave approach was described by Fisher (1955) and Snead (1982) as being important in the evolution of accretionary features, while deposition within wave-shadow zones was recognized by Fisher (1955) and

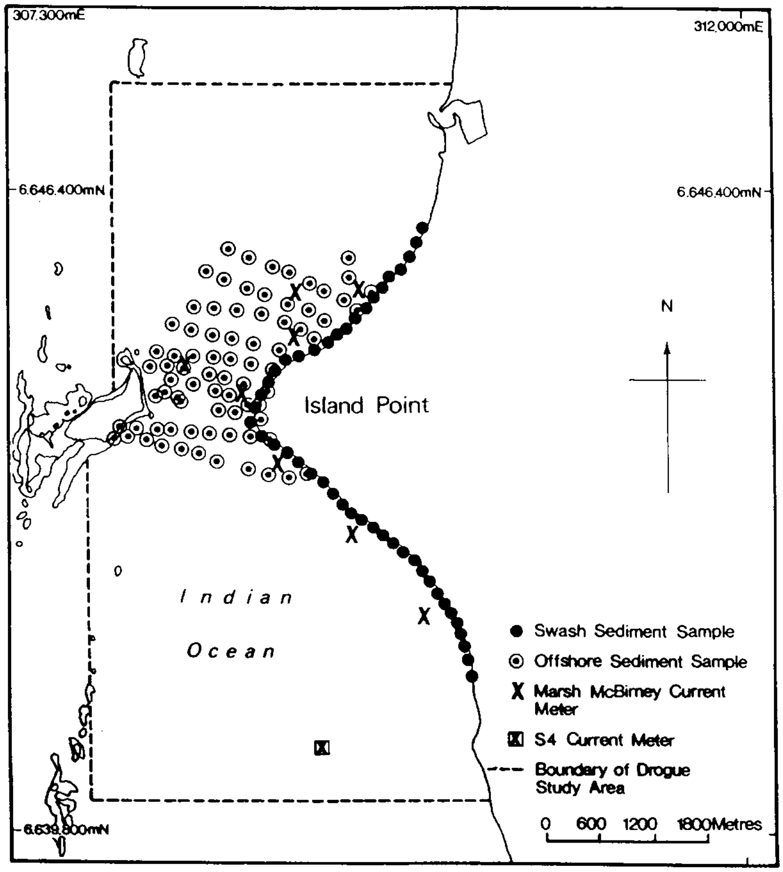

Figure 2. The Jurien cuspate foreland and location of field instrumentation and samples

Zenkovitch (1959) as being important in a number of environmental settings. Storm deposition was addressed by Hey (1967) and High (1975), although the exact role of storms in the evolution of forelands could not be identified without further study. Which of these processes have led to the development of cuspate landform assemblages on the coast of Western Australia is the subject of discussion here.

METHODS

Selection of sites for field study was based on diversity of landforms, their context in the coastal regions, the potential that the sites provided for measurement of nearshore processes, and the extent of previous research in the area. Three cuspate forelands were chosen for close examination: one at Jurien on the central west coast and two from the Ningaloo coast, Winderabandi Point and Turquoise Bay. The cuspate foreland at Island Point, Jurien (Figure 2), has been the subject of previous studies involving offshore sediment transport and Holocene evolution of the foredune plain (Woods, 1983a,b). Shoreline change charts were also available for the Jurien coastline (Public Works Department, 1983) and they indicated considerable change in shoreline position over the historical period. Winderabandi Point (Figure 3) and Turquoise Bay (Figure 4) on the Ningaloo coast are approximately 180 ha and 22·5 ha in size, respectively. The landforms and their locations in relation to the offshore reef structure are geomorphologically different. The Turquoise Bay cuspate foreland is morphologically similar to that of a ‘travelling’ foreland described by Escoffier (1954) from Cove Point, Maryland. As such, it is an important site for consideration of contemporary processes and historical

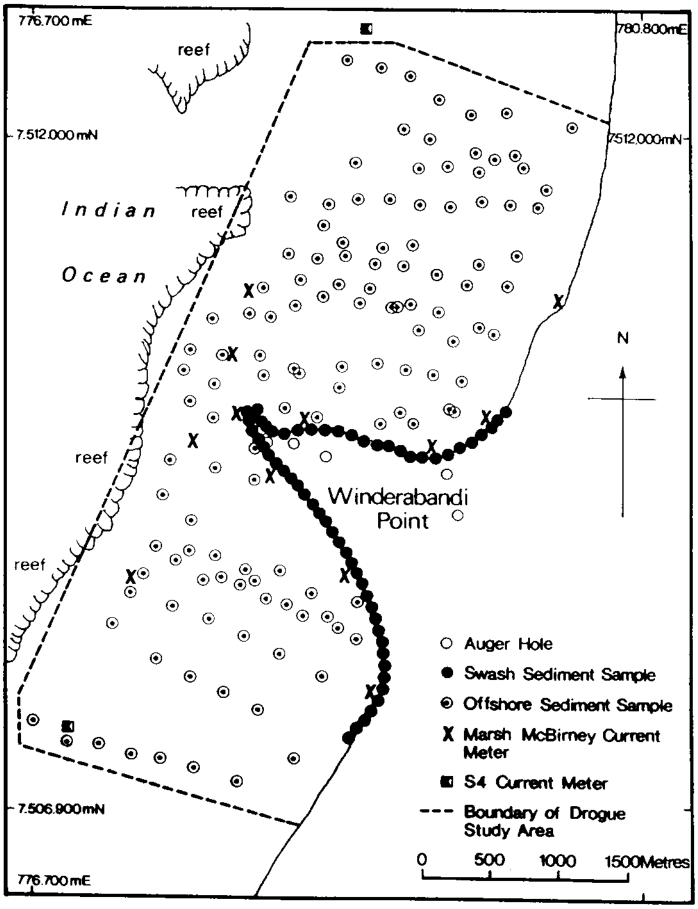

Figure 3. The Winderabandi Point cuspate foreland and location of field instrumentation and samples

change associated with this type of landform assemblage. Winderabandi Point has a more stationary morphology. Neither site on the Ningaloo coast has previously been the subject of specific geomorphological study.

The breadth of this investigation required a wide range of investigatory approaches. Analytic techniques encompassed each of three time scales for geomorphic investigation: palaeoenvironmental, historical and modern studies (Morang *et al.*, 1993). Palaeoenvironmental studies based on stratigraphy and associated geologic principles provide a long-term perspective of shoreline evolution (Boggs, 1987; Morang *et al.*, 1993). Historical studies based on information from maps, photographs and archives allow examination of geomorphic changes that have occurred over a historical time frame, and modern studies based on field data or laboratory experiments are indicative of contemporary processes operating over the time frame of the present study. A comprehensive summary of the studies undertaken at each of the study sites is provided in Table I.

Initially, a review of the regional geology and geomorphology was undertaken to establish the extent of structural control on landform evolution. The historical evolution of the individual cuspate forelands was established through: analysis of historical climate records, primarily wind speed, wind direction and barometric pressure variations at meteorological stations on the Western Australian coast; stratigraphic sampling by auguring of areas of recent accretion; and a review, using GIS techniques, of shoreline position changes from aerial photographs and shoreline change charts.

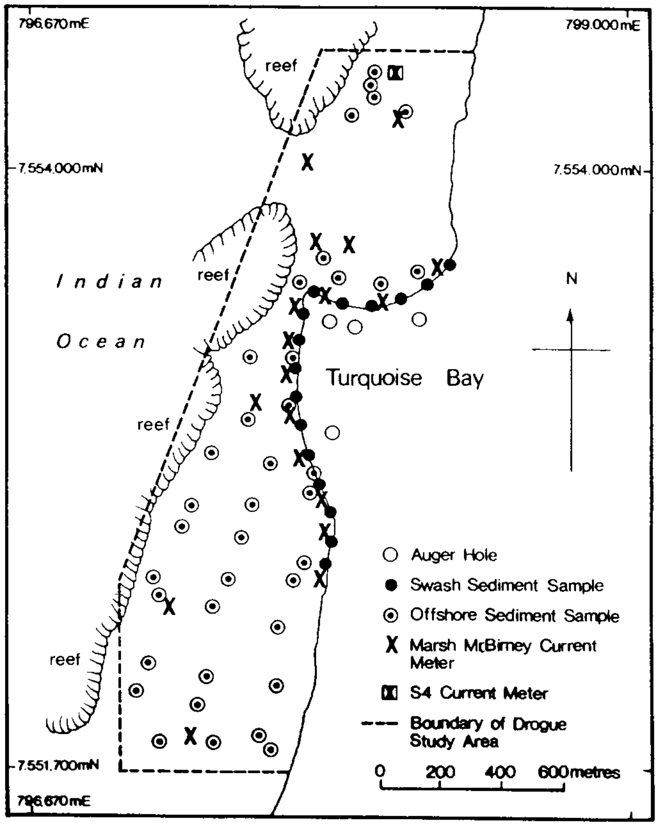

Figure 4. The Turquoise Bay cuspate foreland and location of field instrumentation and samples

Contemporary processes were measured over a series of months at each of the study sites. Surface lagoonal currents were measured using drogues tracked by GPS. Near-bed currents within the coastal lagoons were measured by electromagnetic current meters. S4 current meters were deployed for periods of over three weeks at each of the sites, and longshore currents in the vicinity of the forelands were measured with a Marsh-McBirney electromagnetic current meter. Data from the S4 current meters were subject to harmonic analyses and subsequently used to determine the relative contributions made by tidal currents and longer period events in the lagoonal environments. Sediment transport pathways in the lagoonal areas and alongshore in the vicinity of the forelands were determined following the methods of McLaren and Bowles (1985), Gao and Collins (1991, 1992) and Masselink (1992). Sediments were sampled on a 200 m grid pattern in the lagoon in the vicinity of the forelands and at 100 m intervals along the shore. Grain-size parameters including mean grain-size, standard deviation and skewness were used, in conjunction with the current measurements, to identify the general patterns of sediment movement.

The results presented here are preliminary findings, intended to point the way to future, more thorough investigations of long-term landform evolution and the processes responsible for observed morphology. Certainly, linking contemporary processes to coastline evolution is fraught with difficulties due to the incompatibility of timescales involved. Contemporary processes are the result of external forcing as well as the local coastal geomorphology and geology. They are only to a lesser extent responsible for the observed morphology. An understanding of contemporary processes such as waves, tides and prevailing winds, however, allows the establishment of baseline conditions against which more extreme events and the subsequent response of landforms may be measured. In the case of more extreme events, although storm processes were not measured at any stage in the field project, consideration of the historical evolution of the landforms and the possible effect of storm surge aids interpretation of processes contributing to the evolution

Table I. A summary of the field and laboratory investigations undertaken at each study site

Study site	Island Point, Jurien	Winderabandi Point	Turquoise Bay
Review of regional setting	Understanding of the regional geomorphology and geologic setting was based on field observation and a review of published literature.	Characterization of the local geomorphology and geology was based on field observation, published literature and aerial photograph interpretation.	Characterization of the local geomorphology and geology was based on field observation, published literature and aerial photograph interpretation.
Stratigraphic sampling and profile morphology	No field work undertaken. A review of Holocene stratigraphy was provided by Woods (1983a)	Six locations were investigated through hand augering. Profiles were measured across the beach ridges and parabolic dunes.	Four locations were investigated through hand augering. Profiles were measured across the beach ridges and foredunes.
Historical climate trends	Historical climate trends were established from analysis of data obtained from the Western Australian Bureau of Meteorology for Jurien (1970 to 1994). Data included wind speed, wind direction and barometric pressure at 6 hourly intervals.	Historical climate trends were established from analysis of data obtained from the Western Australian Bureau of Meteorology for Carnarvon (1949 to 1995). Data included wind speed, wind direction and barometric pressure at 6 hourly intervals.	Historical climate trends were established from analysis of data obtained from the Western Australian Bureau of Meteorology for Carnarvon (1949 to 1995). Data included wind speed, wind direction and barometric pressure at 6 hourly intervals.
Historical shoreline change	Historical shoreline changes (1875 to 1990) were determined from review of aerial photographs and shoreline change charts.	Historical shoreline changes (1963 to 1989) were determined from review of aerial photographs.	Historical shoreline changes (1963 to 1989) were determined from review of aerial photographs.
Drogue tracking	Drogues were tracked to the north and south of Island Point during January and April 1994.	Drogues were tracked north and south of Winderabandi Point during September and October 1994.	Drogues were tracked north and south of the Turquoise Bay foreland during September and October 1994.
S4 current measurement	One S4 current meter was deployed in the embayment to the south of Island Point during December 1994, June 1995 and January 1996. Measurements included near-bed current speed, current direction and water temperature.	Near-bed currents were measured at two sites in the lagoon (north and south of the point) during September and October 1994. Current speed and direction were recorded at this time.	Near-bed currents were measured at one site in the lagoon to the north of the Turquoise Bay foreland during September and October 1994. Current speed and direction were recorded at this time.
Marsh McBirney current measurement	Current velocities were recorded at six nearshore and two offshore locations during January and April 1994.	Current velocities were recorded at nine nearshore sites and at four offshore locations during September and October 1994.	Current velocities were recorded at 11 nearshore sites and at seven offshore locations during September and October 1994.
Offshore sediment sampling	Sediments were collected from 78 offshore sites in the vicinity of Island Point during April 1994.	Sediments were collected from 127 offshore sites in the vicinity of Winderabandi Point during October 1994.	Sediments were collected from 39 offshore sites in the vicinity of Turquoise Bay during September 1994.
Alongshore sediment sampling	45 swash zone sediments were collected from the northern and southern flanks of the Jurien foreland during April 1994.	57 swash zone sediments were collected from the northern and southern flanks of Winderabandi Point during October 1994.	16 swash zone sediments were collected from the northern and southern flanks of Turquoise Bay during September 1994.

of morphological systems in low-wave-energy coastal settings. The geological setting of the study sites provides the framework in which long-term evolution of coastlines and accretionary landforms may be considered.

RESULTS

Regional setting

The central west coast of Western Australia extends between Geraldton and Mandurah, 29°S to 33°S, and runs approximately along 115°E longitude. A broken Pleistocene reef chain that shelters the mainland shoreline lies up to 20 km offshore. Further north, the Ningaloo Reef extends from 21°47′S to 24°S and along 113°30′E. The reef tract runs parallel to the coastline for a distance of some 280 km and lies between 1 and 6 km offshore. The geology, geomorphology, climate and nearshore oceanography of the central west and Ningaloo coasts are examined here to provide the context for the broadscale study of the cuspate landforms.

Geology and geomorphology. Differences in the geological evolution of the two regions during the Pleistocene has resulted in development of structurally disparate depositional environments. At Jurien, the lagoonal basin is broad and deep compared to that at Ningaloo. At a simple level, lagoonal depth affects basin hydrodynamics, including local generation of wind waves, seiche activity and nearshore water circulation. In turn, these processes help shape the character of coastal sedimentary landforms. The principal environmental differences between the two regions are summarized in Table II.

Between Guilderton and Dongara (Figure 1), the central west coast is located within a sedimentary basin that has been affected by a series of marine transgressions and regressions (Geological Survey of Western Australia, 1990). As a result, outcropping Pleistocene limestone (the Tamala Limestone) now provides the underlying structural control for deposition of beachface and lagoonal sediments, in addition to influencing the nearshore wave and current regime. Onshore, the surface features of the limestone have been modified by accretion of Holocene dunes, beach ridges and banks. Offshore, the unit outcrops as islands or as partially submerged reef platforms. It has been subject to continuous working by incident waves, leading to erosion and collapse of some sections. Between the reefs and shore, the nearshore waters are generally less than 10 m deep but feature a series of marine basins, or deep lagoonal features (depth >10m), separated by ridges of reef and shallow sand banks. The coastal geomorphology is thus structurally controlled by the occurrence of the Tamala Limestone, and the coastline is markedly sheltered from the direct effects of ocean swell.

To the north, the regional geologic setting of the Ningaloo Reef and adjacent Cape Range is provided by a series of anticlines which have resulted in the formation of the Cape and other ranges (Wyrwoll, 1990). The Tantabiddi Limestone provides the general geomorphological setting and much of the geological structure of the coastline (Wyrwoll, 1990). The contemporary fringing coral reef has formed on an offshore limestone platform. It constitutes a broad coral reef flat, up to 100 m wide, that outcrops extensively and close to mean low water spring tide level. Tides and wave action, particularly during high tide conditions, overtop the reef. Its seaward margin is steeply sloped and drops to deep water with depths of over 100 m. To landward, the reef encloses a narrow lagoon, up to 6 km wide, with patch reef and coral outcrops. The waters of the lagoon are shallow and generally less than 5 m deep.

The coastal margin of the Ningaloo Reef has a narrow Holocene beach-dune fringe, which in places is unstable and obscures the original shore-parallel dune ridge morphology. It is occasionally interrupted by Pleistocene limestone outcrops and in some instances the outcrops have provided a focus for sediment accretion and progradation of accretionary structures. Small shoreline salients and several very large cuspate forelands have formed along the shoreline in the shelter of the fringing reef. The large forelands include Winderabandi Point, Sandy Bay, Turquoise Bay and Jurabi Point. They consist mainly of Holocene carbonate-rich sediments.

Climate and Oceanography. Structural differences between the lagoons of the central west and Ningaloo regions determine the relative intensities of oceanographic processes affecting each coast. In both instances, the reefs markedly attenuate waves from the open ocean. On average, 39 per cent of the incident swell energy is dampened by the multiple lines of offshore reef along the central coast (Steedman, 1977) and local

Table II. Principal environmental differences between the central west and Ningaloo coasts of Western Australia

	Central west coast	Ningaloo coast
Reef	• Location between 2 and 5 km offshore • Discontinuous reef lines • High variability in breadth of the reef crest	• Located *c*. 2 km offshore • Semi-continuous reef with few breaks • Broad platform (up to 50 m wide)
Lagoon	• 2 to 5 km wide • Up to 12 m deep • Contains patch reef and sand sheets with extensive algal and seagrass meadows	• 1 to 2 km wide • Up to 5 m deep • Contains patch reef and sand sheets with outcrops of coral reef
Winds	• Southwesterly winds prevail throughout the year • Northwesterly storms occur in winter in association with mid-latitude depressions • Strong sea breezes occur, particularly in summer	• Southeasterly to southwesterly winds prevail throughout the year • Major storms are infrequent tropical cyclones • Southerly sea breezes occur through the year
Waves	• 40 to 70% attenuation of southwesterly swell and open-ocean wave energy • Small to moderate waves (0·2 to 0·5 m) generated inside the lagoon • Seiche activity noticeable	• 70 to 90% attenuation of southwesterly and open-ocean wave energy • Wave pumping across reef flats with changes in tidal conditions • Small waves (0·1 to 0·2 m) generated inside the lagoon
Currents	• Cellular circulation in the embayments with net drift to the north • Low current velocities in the lagoons (<10 cm s^{-1}) • Fastest currents are associated with sea breeze and southwesterly storm generation of longshore currents along the southern flank of the cuspate foreland • Current velocities in lagoons vary from basin to basin but are up to 50 cm s^{-1} • Fastest currents are associated with sea breeze and southwesterly storm generation of longshore currents along the southern flank of the cuspate foreland	• Cellular circulation in the embayments with net drift to the north, and with marked discharge seaward through gaps in the reef • Current velocities in lagoons vary from basin to basin but are up to 50 cm s^{-1} • Dominant tidal signature in the near-bed currents • Strongest currents are tidal currents entering and exiting the lagoon
Tides	• Tides are micro-scale and are mixed, mainly diurnal in form • Spring tide ranges are <1 m	• Tides are micro-scale and semi-diurnal in form • Spring tide range is 1·8 m

topography may cause greater attenuation of the prevailing southwesterly swell (Hegge, 1994; Lemm *et al.*, 1999). At Jurien, the attenuation is close to average conditions. Although no measurements are available, the proportion of attenuation is observably higher along the Ningaloo coast than it is Jurien, and is likely to be closer to 90 per cent. In both instances, wind waves generated in the lagoonal waters provide a significant component of the energy spectrum and second-order wave motions, such as shelf waves and seiches, are important contributors to the energy regimes.

The wind regime of the two regions is also different, especially with respect to the frequency and intensity of storms and the incidence of sea breeze activity. The west coast of Western Australia encompasses a range of climatic conditions due to its latitudinal extent. Weather conditions are generally determined by movement of a belt of anticyclonic high pressure systems which shift seasonally between latitudes 26°S and 45°S (Gentilli, 1971). The more northern location of the subtropical highs in winter allows mid-latitude low pressure systems, which are often associated with cold fronts, to bring northwesterly to westerly winds and large swell to the central west coast. Prevailing winds in summer are easterly to southeasterly at Jurien.

The Ningaloo coast is at the northern extent of the influence of the anticyclones in summer, and lies within their path in winter. This region therefore experiences quiescent weather conditions during summer but in

Table III. Percentage frequency of onshore winds in the central west and Ningaloo coastal regions. Data were obtained from the Western Australian Bureau of Meteorology. Data presented here are based on 28 and 48 years of record for Jurien and Carnarvon, respectively

Season	Frequency of S to SW winds	Frequency of N to W winds	Frequency of S to SW winds >30 km h^{-1}	Frequency of N to W winds >30 km h^{-1}
Jurien–summer	82	8	37	1
Jurien–autumn	60	21	11	3
Jurien–winter	33	43	3	9
Jurien–spring	69	22	15	4
Carnarvon–summer	84	13	37	1
Carnarvon–autumn	78	14	15	1
Carnarvon–winter	60	23	8	2
Carnarvon–spring	84	14	35	2

Table IV. Tide ranges (in meters) for the central west (Jurien) and Ningaloo coasts (Exmouth) (Department of Defence, 1995)

Location	HAT*	MHHW*	MLHW*	MSL*	MHLW*	MLLW*	LAT*	Tide type
Jurien	1·2	0·8	0·6	0·5	0·5	0·3	0·0	Mixed, predominantly diurnal
Exmouth	2·8	2·3	1·7	1·4	1·1	0·5	0·0	Semi-diurnal

* HAT = Highest Astronomical Tide; MHHW = Mean Higher High Water; MLHW = Mean Lower High Water; MSL = Mean Sea Level; MHLW = Mean Higher Low Water; MLLW = Mean Lower LowWater; LAT = Lowest Astronomical Tide

winter and spring the anticyclonic belt brings strong easterly to southwesterly winds to the area. Occasional tropical cyclones bring gale force winds to the region. From 1907 to 1993, 79 tropical cyclones passed through the 5° latitude/longitude grid including Exmouth at 110–115° east and 20–25° south. The grid areas to the north, northeast and east have corresponding counts of 112, 116 and 81 tropical cyclones in the same period. The former two are indicative of the number of cyclones that track along the northwest shelf rather than crossing the shore (M. Eliot, personal communication). In contrast, tropical cyclones occur only once every 10 years near Jurien. Surge associated with the passage of the tropical cyclones is considered to be significant in evolution of the coastal systems; however, wave and water level heights and the extent of overwash on the beach and in foredune areas have not been measured during a storm or tropical cyclone event. Observations of wrack deposited as overwash fans in the foredunes and significant erosion of beach and foredune sequences in response to storm conditions have been reported elsewhere (Sanderson *et al.*, 1998).

Strong sea breeze conditions with wind speeds in excess of 30 km h^{-1} are experienced in summer at Jurien and in late winter, spring and early summer on the Ningaloo coast. Hence there is a longer season of sea breeze activity at Ningaloo than at Jurien. A summary of the percentage frequency of onshore winds at Jurien and Ningaloo is provided in Table III. Jurien Bay experiences micro-scale tides which are mixed, mainly diurnal in form, and with spring tidal ranges less than 1 m. In contrast, the tidal regime of the Ningaloo coast is semi-diurnal, with 1·8 m tides being experienced during spring cycles (Department of Defence, 1995). The full range of tides is indicated in Table IV.

Incident wave energy along most of the Western Australian coast is largely determined by the nature of the protection offered to the shoreline by offshore reef chains and islands. At Jurien, the offshore wave climate is dominated by swell with an average significant wave height of 1·5 m (Lemm *et al.*, 1999). Wave energy conditions during summer and autumn are relatively low and remarkably constant. Wave energy is greater and highly variable during the winter–spring period and significant interannual variation is possible (Riedel and Trajer, 1978). Swell is predominantly southwesterly, and contributes to a northerly movement of sediment along the seaward side of the reef chain and a net northerly longshore drift along the shore. The

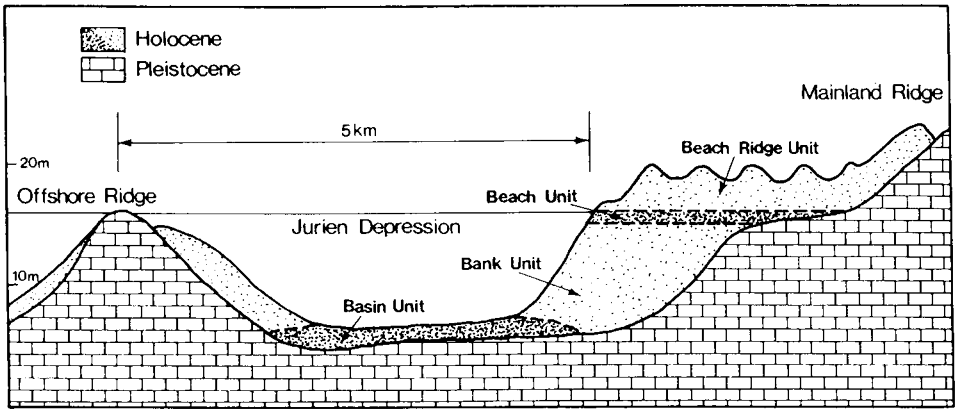

Figure 5. Stratigraphy of the Jurien coastal plain

inshore wave energy is considerably less than the offshore wave energy due to dissipation of energy through diffraction around reefs and islands, as well as through wave breaking and reflection by the reef system (Silvester, 1987; Hegge *et al.*, 1996). The wave climate which therefore characterizes the central west coast lagoonal environment is mostly composed of highly variable wind waves generated close to shore.

Very little wave data have been collected from waters adjacent to the Ningaloo coast. However, Silvester and Mitchell (1977) determined that offshore, southerly swell with heights of 1–2 m is common in summer, with heights increasing to 2–3 m in winter. Some low energy waves are incident from the north and northwest during autumn and winter. Extreme wave characteristics are generated by tropical cyclone activity but are experienced infrequently. Inside the lagoon, onshore winds such as the strong sea breezes generate short, steep sea waves with heights of 1 to 2 m and periods of 4 to 6 s. These wind waves are the dominant wave conditions landward of the reef crest due to the protection provided by the extensive fringing reef.

Case studies

Island Point, Jurien Bay. The cuspate foreland at Jurien lies within a sedimentary basin characterized by a series of shoreline and dune deposits. The stratigraphy of the foredune plain and its adjacent region has been described by Woods (1983a). It comprises a series of Holocene units overlying the Pleistocene Tamala Limestone. Along the coastal margin, Holocene sediments overlie the limestone at variable depths and reach a maximum thickness of 15 to 18 m beneath the Jurien town-site. Sediments of the lagoon basin are defined separately from the beach ridge, beach and offshore bank units (Table V, Figure 5).

Progradation of the emergent foredune plain at Jurien occurred on both the northern and southern flanks of the foreland until 2400 years BP, after which time sedimentation was confined to the southern region (Woods, 1983a). Westward progradation ceased around 1800 years BP and sediments become progressively younger towards the northwest where the growth of an asymmetrical point with truncated foredune ridges is currently taking place. Erosional episodes during the Holocene have been recorded in the stratigraphy of foredune plains that occur elsewhere in the central west coast region (Shepherd and Eliot, 1995). These episodes are likely to have also occurred at Jurien where scarping of transgressive dune sequences is present, but has not been dated. On the central west coast, including at Jurien, recent shoreline progradation is common on the northern flanks of sedimentary promontories, in north-facing embayments and where the sedimentary material is largely protected from erosion associated with southerly wind-wave activity (Maxwell, 1995). Accretion of sediment on the northern flank of the Island Point foreland has occurred over the past 115 years and particularly since 1978 (Sanderson, 1997a). Erosion of the southern flank of the foreland has occurred throughout the historical period, at rates of between 2 and 4 m per year between 1942 and 1992 (Figure 6). Accretion of the asymmetrical point occurred at up to 8 m per year between 1980 and 1992.

Storm activity, here defined as daily average wind speed $>10{\cdot}9$ m s^{-1}, or wind speed ≥ 40 km h^{-1}, has declined and the average annual wind speed decreased slightly from 1970 to 1994, the period for which

Table V. Holocene sedimentary units of the Swan Coastal Plain at Jurien, Western Australia (after Woods, 1983a; Sanderson, 1997a)

Unit type	Location	Sediment characteristics
Shelf unit	Covers the sea floor between the inner and outer ridges and extends offshore past the 20 m isobath.	Sediments derived from eroding Pleistocene outcrops; mainly quartz, lithoclasts and grainstones.
Basin unit	Forms a sheet at the bottom of the Jurien Basin.	Composed of fine material winnowed from active environments; are typically skeletal and quartz dominated with sponge spicules.
Bank unit	Overlies the Basin Unit and forms wedge or elongate mound-shaped bodies that fringe and partition the Jurien Basin. Best developed in zones of swell-wave interference behind offshore features and around the mainland shore (this unit makes up the bulk of the Holocene sequence).	Sediments are derived from the breakdown of offshore ridges and locally produced biogenic material.
Beach unit	This unit overlies the bank unit.	Sediments are bedded, moderately to well sorted, medium to very coarse, skeletal quartz grainstones. The swash zone sands are typically shelly and underlie moderately sorted, medium grained backshore sands.
Beach ridge unit	Forms a horizontal sheet, 1–3m thick, which overlies the beach unit.	Sediments are structureless, well sorted, fine, skeletal and quartz grainstones. The unit is best developed around the mainland shores.
Transgressive dune unit	Forms parabolic dunes that in places overlie the foredune ridge unit and Pleistocene limestones.	Sediments are typically cross-bedded, well sorted, fine skeletal grainstones.

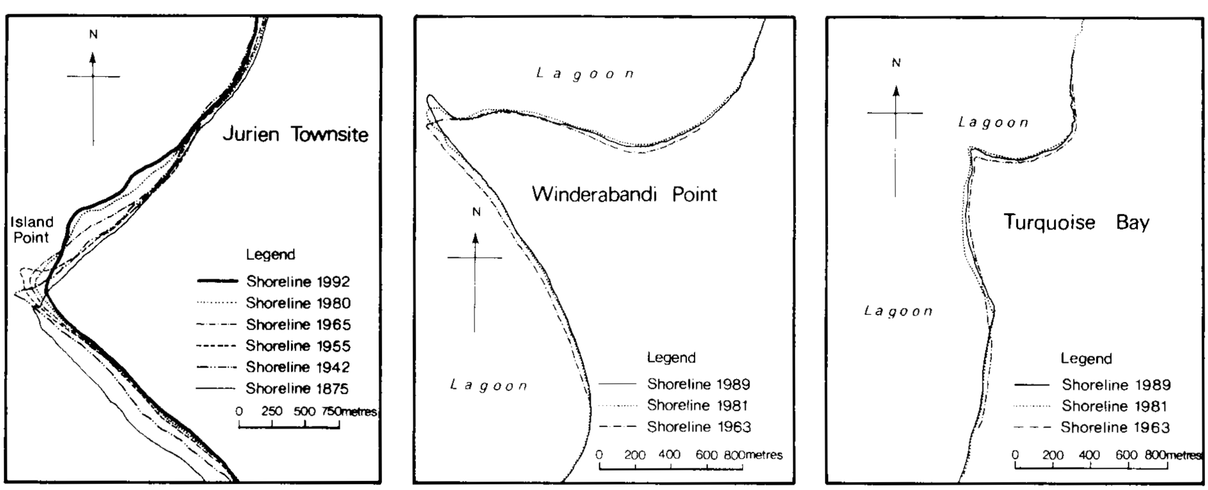

Figure 6. Shoreline change at Jurien, Winderabandi Point and Turquoise Bay

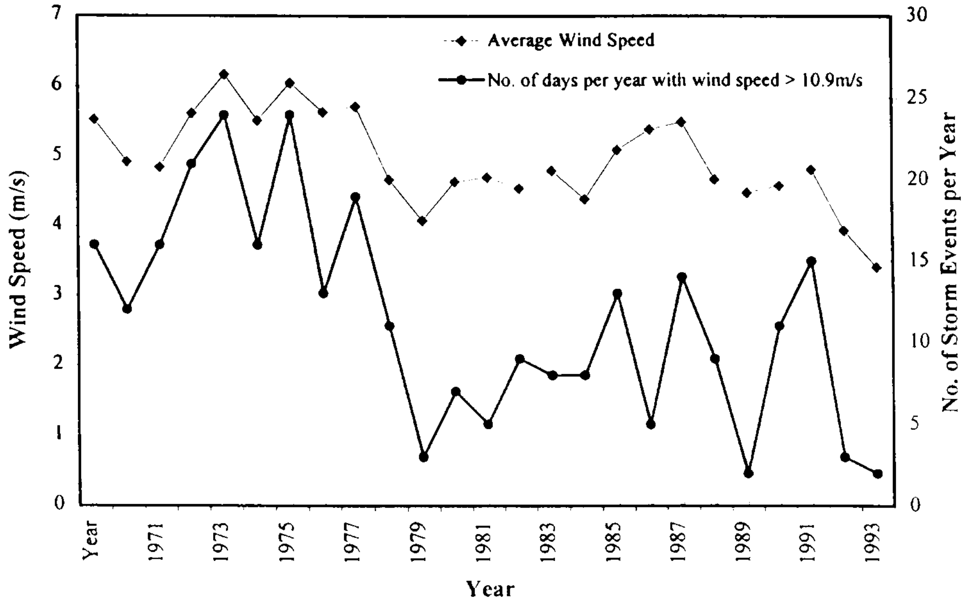

Figure 7. Changes in storm frequency and wind speed at Jurien, 1970–1994

records are available at Jurien. At the same time, the frequency of south to southwesterly winds has increased (Figure 7). This has occurred coincidentally with the changes in shoreline position. It is likely that the combination of decline in northwesterly storm activity and the increase in south to southwesterly winds has contributed to erosion of the exposed southern flank of the foreland and accretion on the sheltered northern flank.

Coastal morphology is affected by changes in wave patterns due to infrequent alteration of reef topography. As previously discussed, the reef system on the central west coast is subject to continual erosion due to wave attack and weakening of the limestone rock structure (Silvester, 1987). Observations by local fishermen indicate that significant reorientation of the point at Jurien took place in response to collapse of a section of the offshore limestone reef chain during intense tropical cyclone activity in 1978. This may be contributing to current realignment of the shoreline and increasing asymmetry of the point that is observed in the charts of historical shoreline change.

Nearshore processes at Jurien are chiefly wind-driven with some tidal forcing and influence from longer period fluctuations such as shelf-wave activity as well as seiching. Limited variability of current speed and direction is apparent in S4 current meter records obtained during summer and winter periods (Figure 8). The mean current was low in both seasons (3·8 to 4·4 cm s^{-1}) (Table VI). The direction was predominantly northwesterly in summer and southwesterly in winter. This corresponds with the variability of wind direction

Table VI. Characteristics of current speed in the lagoonal areas at Jurien, Winderabandi Point and Turquoise Bay

Site	Mean (cm s^{-1})	Maximum (cm s^{-1})	Minimum (cm s^{-1})	Standard Deviation (cm s^{-1})
Jurien–summer	4·4	14·9	0	2·0
Jurien–winter	3·8	12·9	0	2·2
Winderabandi Point–south	12·8	36·0	0·2	6·6
Winderabandi Point–north	8·0	29·7	0	5·5
Turquoise Bay	21·7	48·9	0·2	9·7

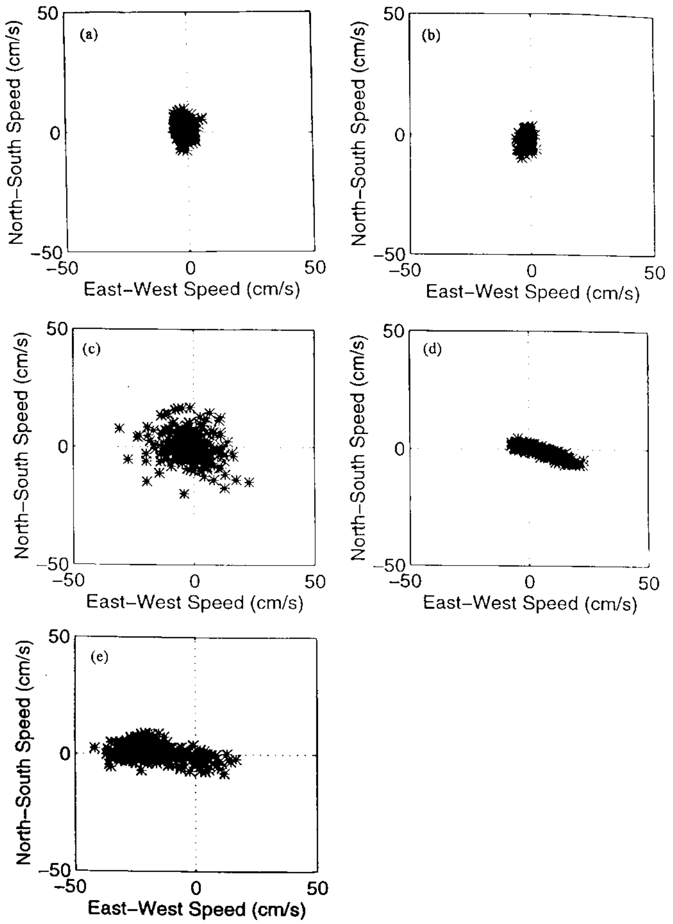

Figure 8. Current speed and direction at the S4 current meter sites. (a) Jurien, Summer; (b) Jurien, winter; (c) Winderabandi Point, south; (d) Winderabandi point, north; (e) Turquoise Bay

throughout the year (Table III). The percentage energy contributed to currents by long period, diurnal, semi-diurnal and high frequency events has been determined following the methods of Pattiaratchi (1985). During summer, diurnal constituents contribute a significant portion (41 per cent) of both the east–west and north–south current variability (Table VII). In addition, long period fluctuations, such as shelf-wave activity, contribute approximately 25 per cent of the measured energy in the north–south direction, while higher frequency events such as seiching contribute a significant proportion of the energy to the east–west current speed. The diurnal cycle is linked to the daily incidence of sea breeze events as well as the tidal cycle. The distinction between currents driven by a diurnal sea breeze cycle and a diurnal tidal signal is made on the basis of harmonic analysis of the current record and the calculation of residual currents, or those driven by factors other than tidal forcing (Table VIII). At Jurien during summer, these residual currents make up almost 60 per cent of the near-bed current speed, thus suggesting that wind forcing by sea breezes and prevailing weather conditions as well as longer period fluctuations are most significant in driving lagoon currents. Longer period oscillations in summer and winter may be related to the passage of the anticyclonic high pressure systems across the coastline and the propagation of shelf waves along the Western Australian coast. The high frequency fluctuations which are apparent in the east–west current records may be attributable to processes such as seiching, which have been shown to occur in the lagoon basin landward of the offshore reef system (Allison *et al.*, 1980).

Table VII. Percentage energy contribution to lagoonal current speed by long-period, diurnal, semi-diurnal and high frequency events

Site	Long period events (<0·25 cpd)	Diurnal events (0·8–1·2 cpd)	Semi-diurnal events (1·8–2·2 cpd)	High frequency events (>3·0 cpd)
Jurien summer: east–west components	16	33	6	23
Jurien summer: north–south components	26	41	6	4
Jurien winter: east–west components	19	11	7	22
Jurien winter: north–south components	20	23	8	15
Winderabandi South: east–west components	1	4	53	24
Winderabandi South: north–south components	1	16	9	26
Winderabandi North: east–west components	1	3	85	7
Winderabandi North: north–south components	3	3	81	11
Turquoise Bay: east–west components	21	1	62	13
Turquoise Bay: north–south components	6	3	20	52

cpd, cycles per day

Table VIII. Residual currents at each of the study sites. Near-bed residual currents were obtained using the Doodson Filter on the S4 current meter data (see Heathershaw and Hammond, 1980)

Current meter location	Residual currents		Representativeness	
	Speed (cm s^{-1})	Direction (°)	Neumann factor	Record length (days)
Jurien–summer	2·5	301	79	27
Jurien–winter	3·1	214	94	12
Winderabandi north	5·8	100	99	16
Winderabandi south	1·8	272	78	17
Turquoise Bay	17·9	274	99	19

The distribution of unconsolidated sediment at Jurien, both within the lagoon and along the shore, was discussed by Woods (1983b) and Sanderson and Eliot (in press). Sediments are deposited along the mainland coast after moving landward over elongate submarine banks extending from the reef chain to the shore. A northern longshore component of sediment movement is enhanced in the narrow and shallow passage between the mainland coast and the offshore island, causing sediment to spill into the northern embayment where it contributes to progradation of the northern flank of the foreland. North of Island Point, longshore transport was found to be significantly reduced, due to shelter afforded by the prograded mainland coast and offshore islands.

Winderabandi Point. At Winderabandi Point, the Pleistocene Tantabiddi Limestone unit provides significant control on patterns of sedimentation and forms the 'core' of the accretionary foreland. This differs from other large cuspate features on the west coast. The others are essentially Holocene features in the lee of geologically older structures which formed as a result of large-scale sedimentation during the late Holocene. However, the position of the foreland at Winderabandi Point was apparently maintained throughout its development phase with sediment accumulating around and over the older structure.

No previous examination of the stratigraphy of forelands has been made on the Ningaloo coast. Preliminary investigation of the stratigraphy of areas of recent sediment accretion at Winderabandi Point is reported here. Fine aeolian sediments are common in the upper horizons at all locations studied and are readily

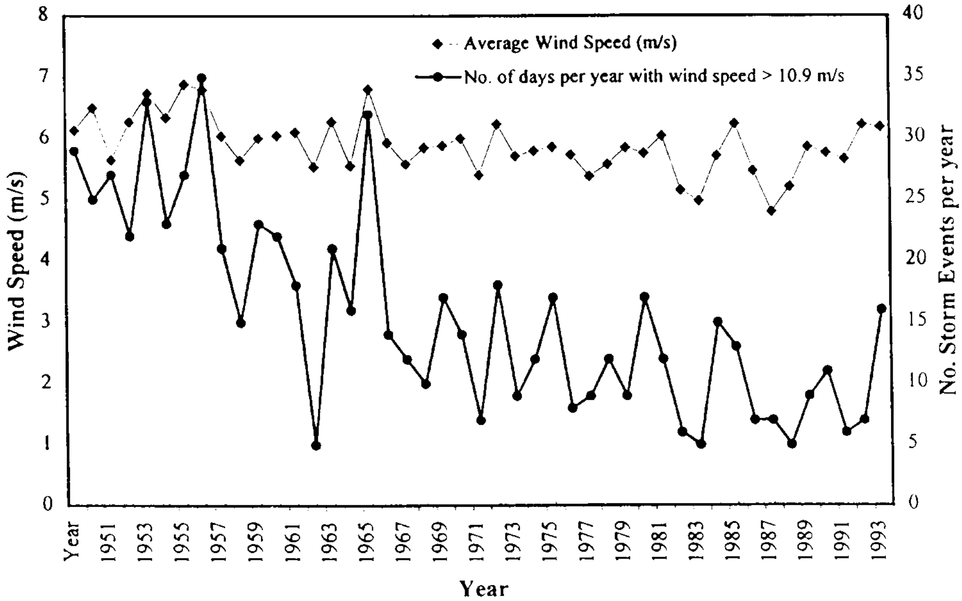

Figure 9. Changes in storm frequency and wind speed at the Ningaloo Reef, 1950–1995

distinguishable from coarser swash and subtidal sediments. Movement of the spit at the westernmost extension of the foreland has been accompanied by accumulation of material that closely resembles modern intertidal sediments from the same area. These sediments are characterized by a higher content of skeletal remains and moderately abraded grey sands. Coarse material, including large shell and coral fragments, is present at groundwater level in areas of recent progradation, particularly where beach ridge development has occurred. On the active beach, the coarse facies is common to the lower swash and adjacent subtidal zones in the stratigraphic column, and may represent beach step deposits that have accumulated under calm weather conditions.

Trends in the historical weather record (1950 to 1995) for the Ningaloo coast (Figure 9) indicate a decrease in storm frequency and wind speed, as well as an absence of extreme events. No significant increase in the occurrence of southerly winds was demonstrated. The record presented here does not clearly distinguish the extreme events, such as tropical cyclones, which occur in the region. However, the wind record does provide a benchmark for future comparison when extreme surge events impact the Ningaloo coast. The pattern of historical shoreline change at Winderabandi Point (Figure 6) includes extension of the spit in the point region, slight erosion of the southern flank and minimal progradation in the north-facing embayment. The rate of erosion on the southern flank of Winderabandi Point is markedly less than at Jurien, although general trends in the patterns of shoreline movement are similar. Erosion of the southern flank occurred at rates of up to 1 m per year from 1963 to 1989. In contrast to this, accretion of up to 4 m per year occurred in the northern embayment between 1963 and 1981. It was followed by a minor phase of erosion from 1981 to 1989.

Nearshore currents were measured at two locations within the lagoon at Winderabandi Point: to the north and the south of the point (Figure 8). Significant variation in current direction and speed occurred at both sites (Table VI). The complex reef structure, tidal flow and currents driven by wave set-up over the reef combine to produce lagoonal currents that are dissimilar to those at Jurien Bay. Spectral analysis of the data indicated a number of dominant components. South of Winderabandi Point the major identifiable contributions to east–west current energy were from the semi-diurnal and high frequency fluctuations. These relate to the semi-diurnal tidal regime, reef set-up-driven currents modulated by tidal water levels over the reef, and processes such as basin seiching. The north–south current energy was dominated primarily by high frequency

fluctuations, with some contribution from diurnal cycles (16 per cent). This may be related to the southerly winds of the daily sea breeze, although this has not been distinguished from a tidal signal in this case.

Semi-diurnal fluctuations in both the east–west and north–south components were identified as the dominant vectors in the northern embayment at Winderabandi Point. These variations in current speed contributed in the order of 85 per cent of the current energy in the east–west direction and 81 per cent of the current energy in the north–south direction. Scatter plots of current speed and direction indicate a strong reversal of flow with little variation outside the flow axis. Further, harmonic analysis of the data (Table VII) indicated that the semi-diurnal tidal constituents were more significant than the diurnal constituents. Residual currents (Table VIII) were significantly less than the M_2 and S_2 tidal currents, suggesting a dominant tidal forcing of the current regime.

These analyses and consideration of regional climate and tidal regimes suggest that currents in the lagoonal environment adjacent to Winderabandi Point are driven by tidal energy, fluctuating water levels over the reef tied to tidal cycles, with some wave forcing. The relative contribution of tidal components and wind-driven circulation is locally variable and dependent on reef configuration, the depth of the lagoon and the location of gaps in the reef. Wind forcing of lagoonal currents is likely to be highly changeable throughout the year, with current flow responding to changes in weather patterns and wind conditions.

Contemporary sediment transport at Winderabandi Point was onshore along the southern flank of the foreland, in the embayment and along the shore. Sediments move past the point, being driven between the mainland and the back reef platform by strong currents. They then spill into the northern embayment and accumulate in the area of foredune development on the northeast shore of the point. Some sediment may be moved further north along the coast.

Turquoise Bay. Control on landform evolution by a core of Tantabiddi Limestone is not evident at Turquoise Bay. The highly asymmetric morphology of the foreland, together with the presence of a series of truncated foredunes, suggests an arrested migratory phase during the development of the foreland. Escoffier (1954) reported similar morphology from cuspate forelands in the narrow channel of Chesapeake Bay, USA. He pointed out that such forms may be characteristic of long narrow bodies of water, and that they would travel parallel to the long axis of the lagoon. At Turquoise Bay, the reef crest is located between 600 and 1200 m offshore, the closest for all forelands examined. Its proximity further constricts water flow in the narrow lagoon. Under these conditions, the foreland may have been driven northwards by the prevailing currents in conjunction with erosion from its southern flank and deposition on its northern margin.

The stratigraphy of unconsolidated sediments comprising the Turquoise Bay foreland is similar to that at Winderabandi Point. Fine aeolian sediments were abundant in the upper horizons at all locations, and coarse material was noted at groundwater level on the southern flank of the foreland. On the northern flank, however, the foredune ridges were composed primarily of fine, well sorted material throughout the stratigraphic column.

Shoreline movement at Turquoise Bay during the period 1963 to 1989 was limited. It involved noticeable accretion of the southern shores between 1963 and 1981, followed by little change from 1981 to 1989. In the northern embayment, the trend in shoreline position has been progradational, although some erosion ($< 0{\cdot}5$ m per year) occurred between 1981 and 1989. These observations suggest that the foreland is in a stationary phase of its evolution.

Currents in the lagoon to the north of the foreland were predominantly westerly, with little variation in direction (Figure 8). One S4 current meter was located landward of, and close to, the main gap in the fringing coral reef. Currents were dominated by a westerly flow of water exiting the lagoon, even during flood tides (Table VI). East–west currents were driven by long-period and semi-diurnal fluctuations, while the north–south components were dominated by semi-diurnal and high frequency events (Table VII). The semi-diurnal tidal regime and currents driven by reef set-up are modulated by sea level. These are the driving mechanisms for circulation within the lagoon but other factors such as seiching and changing wind conditions play a minimal role in the flow of water within the shallow lagoon. The westerly residual current in the lagoon was greater than the tidal constituents (Table VIII). This indicates that the lagoonal flow is driven not only by tidal currents but by water exiting the lagoon, following wave set-up across the reef. Further research is required to quantify and model these contributions.

At Turquoise Bay the opportunity to determine trends in sediment transport was limited by a pavement reef on the seabed and the number of samples collected. Also, an extensive offshore sampling regime was not possible due to constraints placed on navigation by the shallow reef environment. Sediments were generally identified as moving towards the deeper regions of the northern embayment (Sanderson, 1997b). This area appears to act as a local sink, with the main influx of sediment driven by prevailing wind and current patterns from the south. The observed current pattern and aerial photography indicate that a significant amount of sediment may exit the lagoon through the reef gap north of the foreland and be lost from the nearshore system at this point.

DISCUSSION

The amount and nature of data describing the Holocene evolution of the large forelands on the west coast of Western Australia are highly variable. This makes comparison between landforms and regions from an evolutionary perspective problematic. The past and future development of the forelands may, however, be considered in the context of their reef settings, and this provides some insight into the longer-term constraints on morphological evolution. The central west coast has a degrading reef system and in the past it is likely to have been more extensive, with less gaps and higher elevation. As a result of ongoing wave attack and erosion in the future, the reef system will become less extensive, with more gaps and lower elevation. Shoreline configuration and zones of sediment deposition respond quite rapidly to changing inshore wave regimes as a result of alteration in the reef topography. Variability in weather patterns and long-term changes in storminess are also important in the consideration of factors driving coastal evolution on the central west coast.

On the Ningaloo coast, the fringing reef is alive and growing. In the past, the reef would have been less extensive and in the future the reef will continue to provide substantial shelter to the coastline from the offshore swell. As such, variability in shoreline configuration may be more closely related to the impact of extreme events and the geological setting at each site, rather than to any change in wave regime. The growth of the reef system along the Ningaloo coast over the Holocene and the associated increase in mobile marine sediments is also related directly to the size of forelands found in this region. The Winderabandi Point foreland consists of Holocene sediments overlying a Pleistocene core. As the reef system developed, sediments became more plentiful and accumulated behind coherent sections of reef. The Turquoise Bay foreland is composed entirely of Holocene sediments which have migrated along the shoreline and accumulated at a point where northerly longshore currents driven by prevailing wind conditions have been balanced by circulation of currents forced by tides and wave set-up across the reef crest.

Historical changes in shoreline position and the orientation of foredune sequences are used here to examine relationships between climate variability, storminess and the evolution of sedimentary landforms along the coast. The reliability of conclusions is directly related to the availability of data. Over one hundred years of shoreline position data are available for Jurien whereas the record at Ningaloo is limited to approximately 30 years. There is consistency in the way in which the systems have changed. Northward sediment transport prevails along the entire west coast of Western Australia, and an increase in wind frequency from the south has led to increased erosion of the southern foreland flanks and truncation of foredune sequences, accompanied by increased accretion of the northern flanks. In the case of Jurien, this pattern has been accentuated by modification of the offshore reef chain by erosion and the focus of sedimentation shifting to the northern embayment. At Ningaloo, the very strong prevailing southerly winds have continued to drive sediments along the mainland coast and into the northern embayment of both Winderabandi Point and Turquoise Bay. Minor erosion on the northern flanks of the forelands may be related to phases of storminess or storm surge events, although the actual contribution of these high energy events to shoreline and landform morphology change has not been measured and is open to question.

Links between climate variability, shoreline position and foreland morphology are only *inferred* for each site. The record of shoreline movement at the three locations is not sufficiently detailed to enable us to determine the actual contribution of storms or phases of storminess to shoreline and morphological change. Radiometric dates for sediments have not been obtained either, making interpretation of morphology and historical changes subject to question. However, the disjunctions in the patterns of beach ridges and

Table IX. Relationships between the plan shape of cuspate forelands, hydraulic geometry of the lagoon basin, wave climate and nearshore current regime

Site	Jurien	Winderabandi Point	Turquoise Bay
Hydraulic radius of lagoon channel (m)	460	230	120
Significant wave height (m)	1·51	0·85	0·58
Average surface current velocity (cm s^{-1})	10–15	15–20	20–25
Maximum velocity of residual currents (cm s^{-1})	3·1	5·8	17·9

truncation in the contemporary dune sequences suggest that the significance of storms should be closely examined in all coastal settings. An important question that cannot be answered from the available data is the degree to which potential migration of cuspate forelands in sheltered waters, such as Turquoise Bay, is arrested by a balance between phases of southwesterly and northwesterly wind activity or by a balance between prevailing wind conditions and circulation of water within the restricted lagoon basin.

A comprehensive understanding of contemporary coastal dynamics is a fundamental part of the requirements for exploring the long-term evolution of the cuspate forelands and their response to changing climatic and nearshore conditions over time. The knowledge of contemporary nearshore dynamics of the central west and Ningaloo coasts of Western Australia has been extended by the present study. Modal or average conditions at the three sites have been established and flow dynamics such as lagoonal current speed and direction, the relative contribution of tidal forcing to nearshore currents and contemporary sediment transport trends have been described. The key findings of the study of contemporary hydrodynamics describe a relationship between the geometry of the offshore reef system, the significant wave height within lagoonal waters, the modal surface current velocities, residual current velocity and the dimensions and shape of the cuspate forelands (Table IX). As the basins become narrower and shallower and the degree of protection increases, the records for the three sites indicate that there is a diminution in wave energy, an increase in the significance of residual currents, an increase in the relative importance of wind waves, particularly those generated by southwesterly sea breezes, and the system becomes systematically asymmetric due to the strength of longshore sediment transport. These findings extend the work of Silvester and Hsu (1993) who described relationships between the geometry of offshore obstacles or islands and the morphology of accretionary forelands.

Although modelling of the contemporary processes provides an indication of the coupling between water circulation patterns and landform morphology, it does not yet enable any inference to be made about the way in which the system is evolving in the long term. Seasonal variability at Ningaloo has not been identified, extreme events were not monitored at any stage and the magnitude and influence of important processes such as shelfwave activity, seiching and storm surge have not been determined. These processes may be very important in an environment such as Ningaloo where its highly sheltered waters are periodically affected by tropical cyclone activity.

The emergence of the cuspate forelands on the Western Australian coast over the Holocene may be compared with previously described landforms from elsewhere in the world. It was noted by Lewis (1932) that a marked change in exposure of a shoreline to the open ocean could explain the formation of the large Dungeness foreland in Britain. The oblique approach of waves to the coastline has been observed in long narrow channels by Lewis (1932), Fisher (1955) and Zenkovitch (1959), among others, and large cuspate forelands or spits have been built by longshore sediment drift and modification of morphology by lagoon currents. Similar morphodynamics to each of these situations are exemplified by the three study sites on the Western Australian coast. While each setting is unique, it is essential to understand the changing exposure of the regional coastline to open ocean conditions over a longer time period as well as the contemporary hydrodynamic process modifying foreland morphology. The effects of storm conditions on coastal depositional landforms remains open to question; however, the work of Hey (1967), Snead (1982) and High (1975) suggests that high energy conditions may be instrumental in both the delivery of sediment to the coast and the shaping of beach and foredune deposits.

CONCLUSION

The original aim of this research was to establish differences in the regional settings and morphology of cuspate forelands on the west coast of Western Australia and to determine possible explanations for the variability as a basis for future research. It is pointed out that the west coast forms are substantially different from the classic tombolos described in the literature, such as by Zenkovich (1967) and King (1972), and which occur on the south coast of Western Australia. The principal finding on the west coast is that forms vary with the geological framework. In the southern part of the west coast, exemplified here by Jurien Bay, the reef system is degrading and becoming more perforate and less extensive over time. On the other hand, in the northern part of the west coast where the Ningaloo Reef runs parallel with the coastline for a distance of over 280 km, the offshore reef is alive and growing. It provides substantial protection to the coastline from offshore wave conditions and restricts exchange of water and movement of sediment to the narrow and shallow lagoon. As a result, the morphology of forelands is substantially controlled by the interaction of tidally and wave set-up driven lagoonal currents with the prevailing longshore drift driven by wind conditions. The offshore wave regime is of less importance in this environment, where the offshore reef crest substantially attenuates swell energy and diffraction and refraction processes are dependent on the location of gaps in the reef crest.

On the central west coast, nearshore processes are dominated by wind-driven circulation in the lagoon, variability in the importance of refraction and diffraction of swell energy through breaks in the degrading reef system and moderate wind-wave activity. On the Ningaloo coast, contemporary hydrodynamics in the lagoon basin are principally related to effects of semi-diurnal tides and wave set-up across the reef, as well as a predominant northerly longshore drift, constricted by the structure of the reef and mainland coast. From south to north along the west coast of Western Australia, the lagoonal basins become narrower and shallower and the degree of shoreline protection increases. At the same time, the importance of residual currents, locally generated wind waves and longshore sediment transport increases. The long-term changeability in accretionary landforms has not been determined as part of the present study; however, review of historical records of climate and shoreline position point to the conditions under which morphology of coastal landforms is likely to change. Storm surge conditions are expected to be significant in the modification of foredune and beach sequences as well as in the mobilization of marine sediments and their transport onshore, in low-wave-energy environments such as those of Western Australia. Finally, it is suggested that this area be the subject of more rigorous investigation, as a next step to a more complete understanding of the variability in landform assemblages in coastal Western Australia, as well as considering more widely the role of extreme events versus modal conditions in maintaining and modifying coastal morphology.

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